DARK HALOS: THE FLATTENING OF THE DENSITY CUSP BY DYNAMICAL FRICTION

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ABSTRACT

N-body simulations and analytical calculations of the gravitational collapse in an expanding universe predict that halos should form with a diverging inner density profile, the cusp. There are some observational indications that the dark matter distribution in galaxies might be characterized by a finite core. This 'core catastrophe' has prompted a search for alternatives to the CDM cosmogony. It is shown here that the discrepancy between theory and observations can be very naturally resolved within the standard CDM model, provided that gas is not initially smoothly distributed in the dark matter halo, but rather is concentrated in clumps of mass $\geq 0.01\%$ the total mass of the system. Dynamical friction acting on these lumps moving in the background of the dark matter particles, dissipates the clumps orbital energy and deposits it in the dark matter. Using Monte-Carlo simulations, it is shown that the dynamical friction provides a strong enough drag, and that with realistic baryonic mass fractions, the available orbital energy of the clumps is sufficient to heat the halo and turn the primordial cusp into a finite, non-diverging core — overcoming the competing effect of adiabatic contraction due to gravitational influence of the shrinking baryonic component. Depending on the initial conditions, the total density distribution may either become more or less centrally concentrated. Possible consequences of the proposed mechanism for other problems in the CDM model and for the formation and early evolution of the baryonic component of galaxies are also briefly discussed.

Subject headings: galaxies: evolution – galaxies: ISM – galaxies: kinematics & dynamics – galaxies: structure – hydrodynamics

1. Introduction and motivation

The formation and structure of dark matter (DM) halos around galaxies and clusters of galaxies poses one of the great challenges to theories of structure formation in an expanding universe. The basic theoretical paradigm was set by Gunn & Gott (1972) and Gunn (1977), and a more detailed analysis considering the dependence on the primordial perturbation field was done by Hoffman & Shaham (1985). The first N-body simulations designed to probe the structure of dark halos indeed confirmed the basic findings of Hoffman and Shaham (Quinn, Salmon & Zurek 1986; Frenk *et al.* 1988), but could not resolve the innermost structure of the dark halos. Higher-resolution simulations showed evidence of a cuspy density profile of the form $\rho(r) \propto r^{-\alpha}$ with $\alpha \geq 1$, down to the res-

olution limit of the simulations (Dubinski & Carlberg 1991; Warren *et al.* 1992; Crone *et al.* 1994), and further limited the exponent of the innermost density profile to $\alpha \approx (1-1.5)$ (Klypin *et al.* 2000; Navarro, Frenk & White 1997, hereafter NFW; Cole & Lacey 1996; Tormen, Bouchet & White 1997; Huss, Jain & Steinmetz 1999; Fukushige & Makino 1997; Moore *et al.* 1999; Jing & Suto 2000). NFW suggested a particular parametric density profile, claimed to be a universal one (independent of halo mass), and characterized by an $\alpha = 1$ cusp and r^{-3}-like decay at large radii. On the theoretical side it has been demonstrated that a cuspy density profile arises inherently from the cold gravitational collapse in an expanding universe (Lokas & Hoffman 2000).

Whether the predicted density cusp is supported or ruled out by observations is subject to debate. Moore (1994) and Flores & Primack (1994) argued that the observed HI rotation curves of gas-rich dwarf galaxies favor a core-halo structure rather than a diverging inner density profile. This has been confirmed by more recent observations of De Blok *et al.* (2001). The DM distribution inferred for spiral galaxies also show large constant density cores (e.g., Salucci & Burkert 2000). Moore *et al.* (1999) coined this disagreement as the 'core catastrophe,' using it as a major argument against the cold dark matter (CDM) model. Indeed, alternative theories for structure formation have been proposed, *e.g.* self-interacting dark matter (SIDM: see, e.g.,Spergel & Steinhardt 2000). Nevertheless, it has been suggested that the inconsistency may reflect the finite resolution of the observations that has not been properly accounted for in the analysis of the HI rotation curves (van den Bosch *et al.* 2000; van den Bosch & Swaters 2000). Moving on to clusters of galaxies, the cuspy density profile agrees with the recent determination of the mass profile from ASCA X-ray observation of A2199 and A496 (Markevitch *et al.* 1999). These cannot be accounted for in the SIDM scenario (Yoshida *et al.* 2000). In addition, gravitational systems are ultimately unstable to heat transport and SIDM models will eventually undergo gravothermal catastrophe, resulting in even more centrally concentrated structures: (Moore *et al.* 2000; Kochanek & White 2000).

Assuming that the theory of cold collapse in an expanding universe is correct, that halos form with a density cusp, and that observations of galaxies indicate that the present day structure has a finite non-diverging core, we discuss a mechanism for resolving the above conflict. Close inspection of the problem at hand reveals that adding a mechanism that enables 'heat' transport to the inner part of the halo would resolve the problem — destroying the inner cold region where the "temperature" inversion occurs. This will lead to the puffing up of the central regions and to the flattening of the density cusp. The aim of this paper is to show that such a mechanism can be naturally formulated within the CDM cosmogony without appealing to 'new physics.'In addition, as opposed to SIDM we have a two component system — with one component (the halo) that is *always* expanding and the other (baryonic) component that is always shrinking. The baryonic component becoming centrally concentrated is not an embarrassment, since galaxies do have disk-bulge-central mass components that are more centrally concentrated than the observed halo structures. In addition, part of the baryonic mass can be lost in subsequent outflow (which is efficient in precisely those galaxies without highly concentrated baryonic components).

The basic scenario envisaged here is one where the gas (*i.e.* baryon) distribution becomes lumpy because of gravitational collapse and cooling on its Jeans scale. Assuming these lumps of gas to be compact enough and their number densities small enough, so that tidal disruption and collisions are avoided over at least a few crossing times, one can consider them as super-particles moving through the smooth (say NFW) background of DM particles. Super-particles experience dynamical friction (DF), losing energy to the inner dark halo and heating it up. The DF dissipates the energy of the gaseous component, but unlike in the case of radiative dissipation, the energy is conserved. Energy lost by the gas through DF is deposited in the inner dark halo and heats it up. For the above scenario to work, we have to establish that: *(a)* the coupling via DF is strong enough to produce, within a few dynamical times, significant effects and *(b)* with realistic gas mass fraction, there is enough energy to heat up the inner halo and to form a core, overcoming the competing effect of the deepening potential well by the shrinking

gas distribution. The semi-analytical Monte Carlo model used is described in §2 and the results are given in §3. A general discussion of the implications and ramifications of the proposed model is found in §4.

2. Method and Model Parameters

A rigorous modeling of the dynamics of collapse and virialization of the DM-gas system demands hyd-rodynamical/N-body simulations starting from cosmological initial conditions and with a very large dynamical range, so that the DF is properly modeled and the gas dynamics allows for the fragmentation of the gas component into individual massive clumps. Present day capabilities, however, only allow for a more modest approach. One could, for example, perform high-resolution simulations (e.g., Moore *et al.* 1999; Klypin *et al.* 2000), and introduce *ab initio* a population of massive super-particles moving through the background DM. Instead, we model the proposed processes in a semi-analytical Monte-Carlo approach, in what amounts to a feasibility study of the proposed mechanism.

Consider a mass M moving with a velocity $\mathbf{V}_M$ through a homogeneous system of non-interacting particles of mass $m \ll M$ and density ρ with a Maxwellian velocity distribution of dispersion σ. The massive particle experience the DF deceleration (e.g., Chandrasekhar 1943; Binney and Tremaine 1987)

$$\left(\frac{d\mathbf{V}_M}{dt}\right)_{\rm DF} = -\frac{4\pi G^2 \ln\Lambda \rho M}{V_M^3}\left(\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}}\exp\left[-X^2\right]\right)\mathbf{V}_M, \qquad (1)$$

where $X \equiv \mathbf{V}_M/\sqrt{2}\sigma$, the Coulomb logarithm $\ln\Lambda$ is defined by $\Lambda = bV_M^2/G(M+m)$ and b is the maximal impact parameter of the two body encounters, usually taken to be the radius of the system. Although highly simplified and mathematically incomplete, this purely local treatment of DF seems, in many situations of interest, to give results which are a reasonable approximation to the true behavior (e.g. Zaritsky & White 1988). The rate of energy loss by a super-particle is $\dot{E} = M(d\mathbf{V}_M/dt)\cdot\mathbf{V}_M$. This defines a timescale, typically significantly larger than the dynamical timescale and related to it through the ratio of total mass to $\eta = M_{tot}/M$. More precisely, at any given time $X \approx 1$, allowing one to approximate it by $\tau_{\rm DF}/\tau_{\rm dyn} \approx (0.75/\ln\Lambda)\eta$, where $\tau_{\rm dyn}$ is the dynamical timescale. In virial equilibrium $\Lambda \approx \eta$, hence $\tau_{\rm DF}/\tau_{\rm dyn} \approx 0.75\eta/\ln\eta$. The local DF timescale will differ significantly from this and will be much smaller in the inner dense regions.

The mathematical model used here is that of a spherical halo of mass M_{DM} with a population of n_g super-particles of mass M. While CDM halos found in N-body simulations are not perfectly spherical, they are definitely not flat objects and can, for our purposes, be reasonably modeled using spherical symmetry. Moreover, the gaseous component will be assumed to be in the form of compact clumps with sufficiently small crossections and extended spatial distribution so that, for the timescales considered, dissipative collisions leading to the flattening of the gas to a preferred plane can be ignored. In spherical symmetry, each particle i represents a smoothed shell of the same mass m_i and at the same radius r_i. Thus, upon sorting the particles according to their distance from the center, the force on the n^{th} particle is given by $\Sigma_{i=1}^{n-1} G m_i/r_n^2$. To avoid numerical instability we use a Plummer softening of 0.1 % the initial halo size.

The numerical model employed here is that of N_{DM} and N_g particles representing the spatial distributions of the DM and gas (*i.e.* super-particles), respectively. We choose to determine N_{DM} and N_g solely by considerations of a reasonable statistical representation of a two-fluid DM and gas system, coupled via DF. Thus all particles have the same mass $m = 1/N$, where $N = N_{DM} + N_g$. In the limit of $M \gg m$, the dynamical interaction is independent of the value of N_{DM}. To complete the statistical treatment, a multiplicative factor F, the 'coupling constant,' is introduced in Eq. (1). It determines M and n_g in a system of total mass M_{tot} and gas mass fraction f_g with the same DF interaction strength as our corresponding statistical representation in terms of m and N_g. The correspondence is made through the following relations: $f_g = N_g/N$, $M = FmM_{tot}$ and $n_g = N_g/F$. For all the models described here the particle numbers are fixed at $N = 10^5$ and $N_g = 10^4$. Therefore, $f_g = 0.1$. The code is written in units of $GM_{tot} = 1$, where G is the

gravitational constant, so that $m = 10^{-5}$. The initial radius of the halo is taken to be 100 in these units.

The initial DM distribution is constructed to follow the NFW density profile $\rho = \rho_s r_s^3/r(r_s+r)^2$ with r_s. Once the total mass is fixed, determining r_s or ρ_s completely determines the halo model. We choose to fix the former quantity (values are given in Table 1). The scaling to physical units exploits the "universal" scaling relations of NFW and is given by

$$[r] = 1.63 M_{DM}^{1/3} h^{-2/3} 10^{-4} \text{ kpc} \tag{2}$$

and

$$[t] = 0.97 h^{-1} \sqrt{M_{DM}/M_{tot}} \text{ Myr}, \tag{3}$$

where M_{DM} is in solar mass and Hubble constant is defined by $H_0 = 100h$ km s^{-1}Mpc^{-1}. Since NFW halo density profiles have the same functional form irrespective of mass, the mass unit can be arbitrarily chosen. The system of units are completely fixed once the gas mass fraction is. One hundred time units will correspond to about 11 central (in the region $r < 10$) dynamical times and the length unit will be about 1 kpc for a halo of 5×10^{11}M$_\odot$.

Each Cartesian velocity component is sampled from a Gaussian distribution with zero mean and variance $\sigma = \sigma(r)$, where σ is obtained by solving the steady state Jeans equation for the radial velocity dispersion, the solution of which can be obtained in terms of elementary functions and quadrature (with boundary condition $\sigma = 0$ as $r \rightarrow \infty$). Gas particles are either sampled from the same distribution or are taken to be homogeneously distributed within a certain radius R_g. In the latter case, their initial velocities are assumed to have a Maxwellian with half of the halo dispersion at R_g, and the combined system is then scaled to virial equilibrium. Systems are left to relax for 600 to 1000 time units (corresponding to about 6 to 10 central dynamical times) without including the effect of the DF.

The density and velocity dispersion of the DM particles are calculated in a 1000 bins of equal numbers and these values are used in evaluating the DF acting on the N_g gas particles using Eq. (1). The average energy lost by the gas particles in a given bin per unit time is updated at fixed time steps $\Delta t = 5$. Multiplied by Δt, this is the energy to be gained by the DM particles of the same bins. At the end of each time interval, the Cartesian velocity components of the DM particles are updated through an additive term chosen from a normal distribution with zero mean and variance $\sqrt{(2/3)E_b/m}$. Here E_b is the energy gained per DM particle.

The integration is advanced using a Runge-Kutta-Merson method with adaptive timestep and predetermined local tolerance. The results were found to converge for tolerances $\leq 10^{-3}$. Because of the strict spherical symmetry, the gravitational field is much smoother than in the 3D case and evolutionary effects are also very slow. After reaching dynamical equilibrium (and in the absence of frictional forces), a system of a few thousand particles may remain virtually unchanged for hundreds of dynamical times. The total energy is conserved to five digits in the absence of DF. When the DF is turned on, the statistical nature of the energy feedback and finite size of the shells causes additional fluctuations. Still the change in the energy did not exceed 0.51% of the total energy, or a few percent of the energy *exchanged* through the DF, and was not systematic.

The results are shown for times up to $T = 1800$ (where $T = 0$ is taken to be the time when the DF starts acting) corresponding to ~ 2 Gyr (or about 18 central dynamical times), although the models have been advanced much further. We anticipate that eventually the clumps' evolution will become dominated by collisions, leading most probably to their destruction through star formation, merging, fragmentation, and other processes which will provide a natural termination to the DF action. For example, for n_g objects of radius d randomly moving inside a radius R_G, the mean free time is $1/3 n_g (\frac{R_g}{d})^2$ crossing times. For the parameters of Model 1 (c.f. Table) and assuming $d \sim r_s/50$ for example, this is about 25 crossing times. Detailed analysis of the aforementioned processes is outside the scope of this paper. Here, we either terminate the evolution at $T = 1800$ abruptly (Models 1, 3, 4), or introduce an exponential cutoff (with characteristic timescale of 400 units) in the coupling parameter F (Model 2).

TABLE 1
MODEL PARAMETERS

Model	F	r_s	Gas at $t=0$	n_g	$M/M_\odot$ (for $M_{DM}=10^{12}M_\odot$)
1	20	5	uniform $R_g=20$	500	2×10^8
2	$100\times e^{-T/400}$	5	uniform $R_g=20$	$100\times e^{T/400}$	$10^9\times e^{-T/400}$
3	20	5	NFW	500	2×10^8
4	100	3	NFW	100	10^9

3. Results

A wide range of models have been calculated but only four models are presented here, the parameters of which are given in Table 1. These parameters are representative yet not exhaustive of the types of systems we have studied. The general trend is the same for all the models: the DF is found to be an efficient mechanism of heating up the DM halo, causing the flattening of the density cusp into a core-halo structure and consequently resulting in less steeply rising rotation curves. In principle, it is possible to have a much smaller $N_g\sim1000$ and to obtain similar results for smaller $R_g\sim5$.

Fig. 1 shows the evolution of quantities characteristic of the matter distribution of Model 1. We note that the final DM rotation curve rises less steeply as the DF puffs up the inner halo. To get a quantitative assessment of the disappearance of the cusp and the emergence of a core-halo structure, the final DM rotation curve has been fitted by Burkert's (1995) profile,

$$\rho=\frac{\rho_0 r_0^3}{(r+r_0)(r^2+r_0^2)},\tag{4}$$

claimed to be a good fit to the DM rotation curves inferred from observations (e.g., Salucci & Burkert 2000).

Assuming the density to be constant, $\rho\approx\rho_0$ inside r_0 and using Eq. 5 of Burkert & Salucci, one finds the observational correlation $\rho_0\propto r_0^{-2/3}$ between the core radius and density. We now note that the change in the rotation curve from a NFW profile to a Burkert profile is the result of a decrease in central density accompanied by heating of the central region and that the region where this mechanism is effective lies inside r_s (as can be seen from the lower panels of Fig. 1). Hence, one expects $r_0\approx r_s$ in the final configuration. In addition, for the density to be fit at large radii, $\rho_0\approx\rho_s$. Moreover, it can be shown (e.g. by using the first four equations of Burkert & Silk 1999 and assuming r_s to be small compared to the virial radius) that $\rho_s\propto r_s^{-9/(\gamma+3)}$, where $\gamma=7.14$ for SCDM models, and $\gamma=10$ for CDMΛ cosmologies. Therefore, especially for $\gamma\approx10$, one is able to anticipate the observational correlation between r_0 and ρ_0 from the theoretical one between r_s and ρ_s obtained from numerical simulations — provided that the DF mechanism is able to wash out the density cusps of halos of all masses.

For comparison, we have studied systems with no feedback into the halo from the gas lumps. In this case, as expected the halo contracts adiabatically, becomes more centrally concentrated and the kinetic energy profile increases self-similarly (Fig. 2). This behavior is thus similar to the case of a smooth gaseous system contracting via dissipational collapse inside the dark matter halo. It is then clear that the major assumption here, leading to the expansion of the host halo, is that the gas is distributed in clumps. The resulting energy feedback is able to overcome the competing effect of adiabatic contraction. The halo thus expands instead of contracting further under the gravitational influence of the shrinking baryonic component.

It is possible to obtain nearly identical results for larger coupling parameters (thus higher clump masses M) acting on much shorter time scales, as in the case of Model 2, where an exponential cutoff in the two-fluid coupling (parameter) was implemented. This can be interpreted as representing

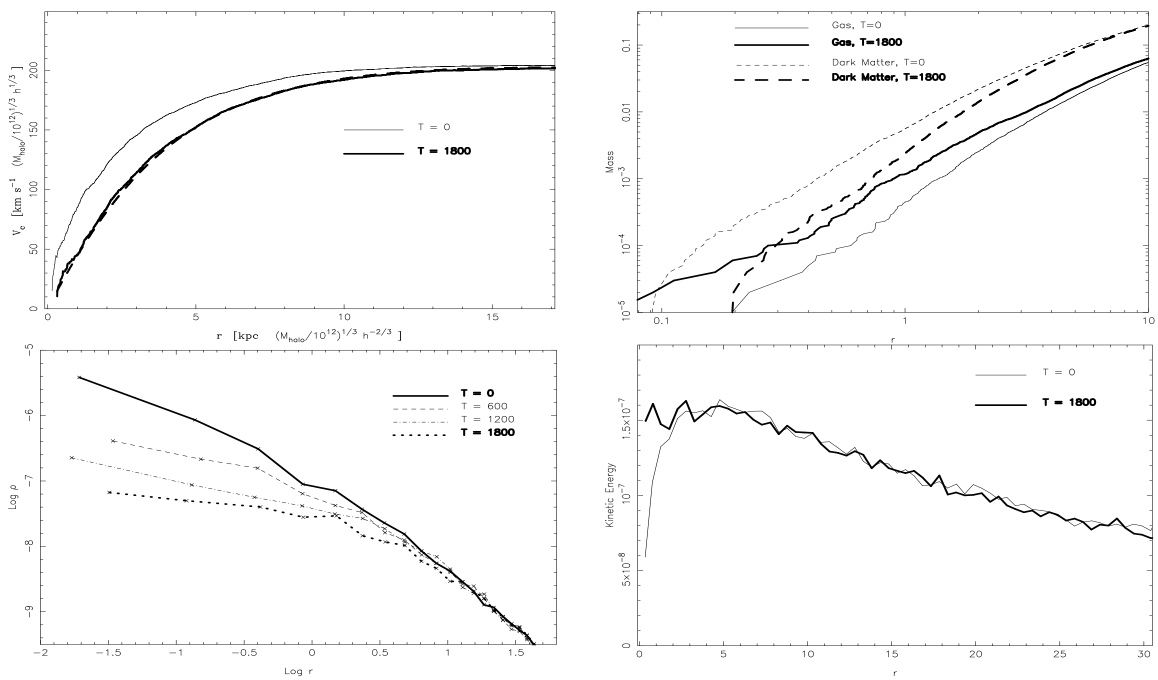

Fig. 1.— Evolution in central region of Model 1. Top left: Initial and final DM rotation curves. The dashed line is a least squares fit using Eq. (4). Top right: Initial and final gas and DM cumulative masses. Bottom left: DM density at four different times. Bottom right: Initial and final kinetic energy per DM particle.

a fragmentation process.In both Models 1 and 2, the inflow of clumps due to energy loss via DF is small enough so that the *total* density in the inner regions also decreases and the total rotation curves can still be fit with Burkert models, as can be seen from Fig. 3. In Model 1, if our process is allowed to continue, it will ultimately cause excessive central gas concentration, so that the total density fit to Eq. (4) will worsen. This is not true of Model 2 however, where due to the exponential cutoff, the the coupling via the DF is already too small at $T = 1800$ to have any significant effect. In all cases however, the DM distribution continues to be fit well by a core-halo profile far beyond the timescales shown here.

The value of F, and hence M, controls the rate at which energy is transported, but the integral quantity depends mostly on the mass fraction in clumps in the region of interest (i.e., inside $r \sim 10$). In the above models, after the initial pe-

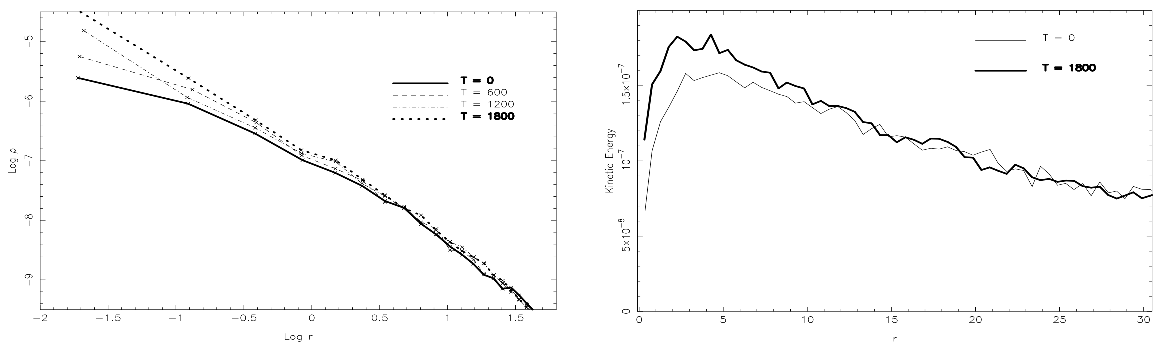

Fig. 2.— Evolution of DM density and kinetic energy per DM particle in Model 1 in the absence of energy feedback.

riod of relaxation, the mass in the gas component comprises about a fifth of the mass in this region distributed in a much less concentrated way than the DM (Fig 1, upper right panel). If the clumps are initially distributed the same way as the DM, their number density will be too small to have a significant effect outside the very central region for $F = 20$. They also have smaller binding energy to give. In such cases it was found that the final rotation curves can be fit by

$$\rho = \frac{C}{(r + r_c)(A + r)^2}, \tag{5}$$

which rapidly converges to the NFW profile for $r > r_c$ — and the requirement that it does so fixes the parameter C. Moreover, it was invariably found that best fits require that $r_c = A$, to very high accuracy, making it a one parameter fit. To compensate for the smaller gas mass fraction, one can increase F or the central density — which increases the coupling *and* decreases the

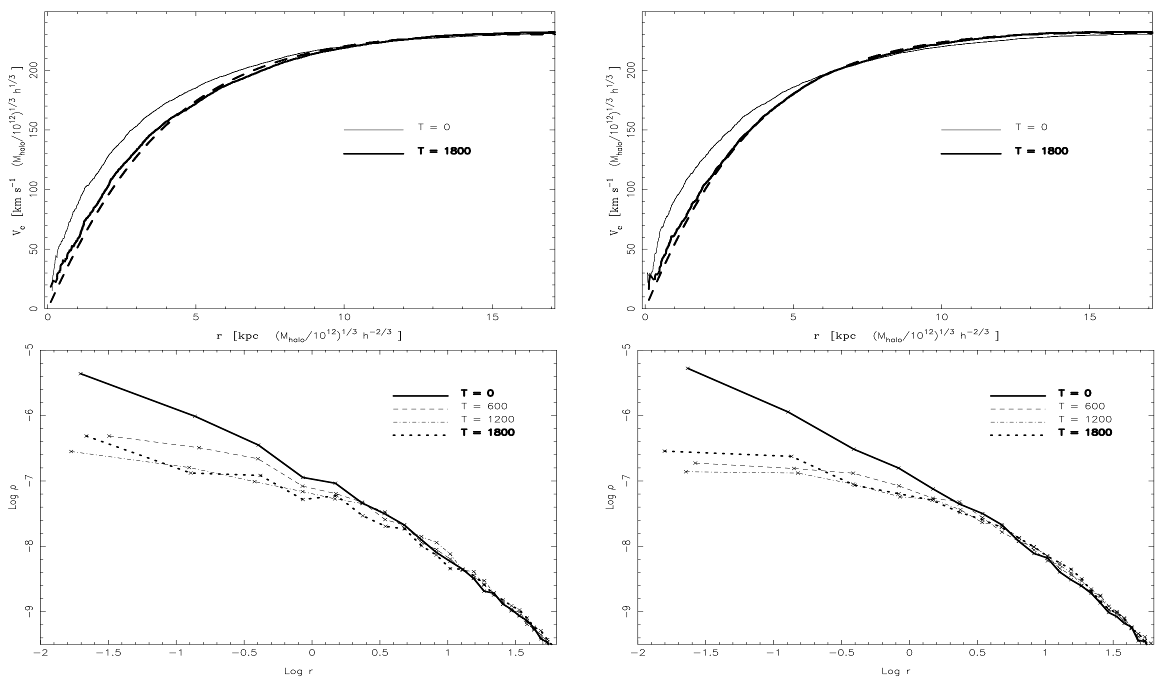

Fig. 3.— Top: Initial and final total rotation curves of Model 1 (left panel) and Model 2. Dashed lines represent fits using Eq. (4). Bottom: The total density profile for the same models given at four different times.

dynamical time, thus rendering the process much faster. In such cases, the final rotation curves at $t = 1800$ can no longer be well fit by Eq. (5): the DM distribution is now modified at intermediate radii and is better fit by Eq. (4) (Fig. 4, upper panels). Another consequence of the strong coupling and condensed initial distribution is that the total density profile is very centrally concentrated (Fig 4, lower panels). This is due to the more concentrated initial distribution and smaller mass, implying smaller amount of binding energy that can be released by the clump system, within a given radius, before it becomes highly concentrated — it could possibly lead to the formation of the galactic bulge/black hole system. This and other possible scenarios for the fate of the clumpy gas will be discussed elsewhere.

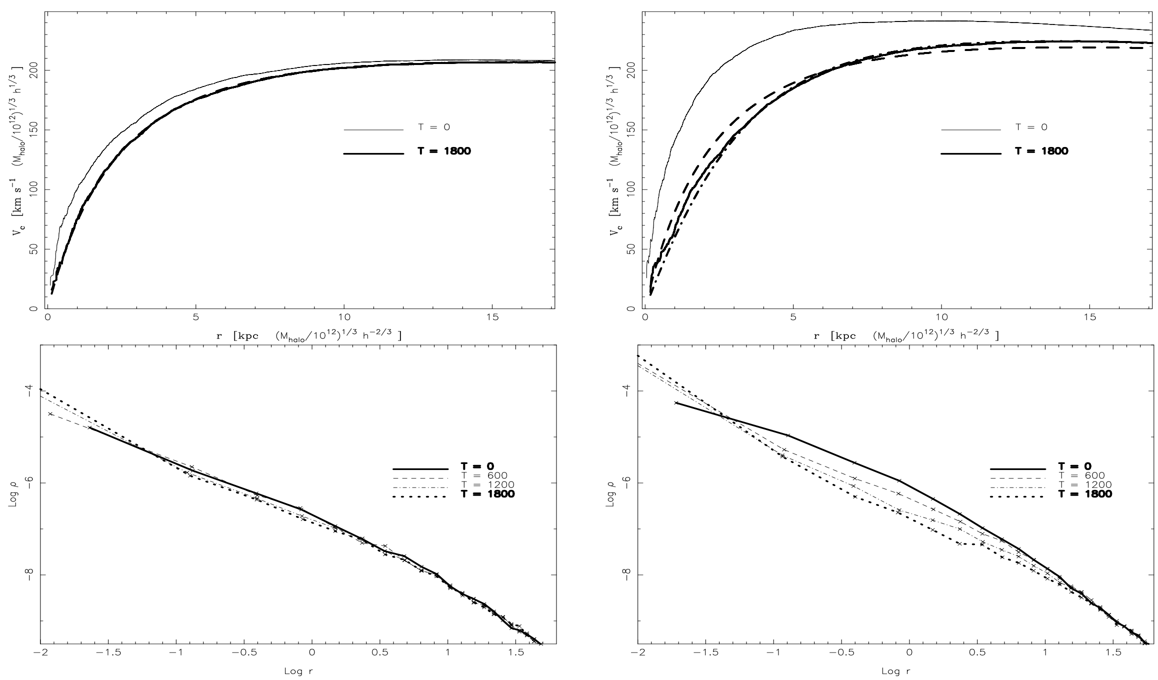

Fig. 4.— Top: Initial and final DM rotation curves for Model 3 (left) and Model 4. Dashed lines represent best fits using Eq. (5), with $R_0 = 2.12$ and $A = 2.14$ for Model 3 and $R_0 = 2.027$ and $A = 2.017$ for Model 4 (in the units defined in section 2). The dashed dotted line in the right panel represents a fit using Eq. (4). Bottom: The total density profiles for the same models given at four different times.

4. Discussion

Starting from the NFW cuspy initial density profile for the halo, we have shown that dynamical friction provides an efficient mechanism for transporting energy from the clumpy component to the dark matter and heats it up. Under a wide range of conditions, the clump orbital energy is sufficient to flatten the density cusp and to form a core-halo structure. Although we assume that 10% of the total mass is in the clumpy component, in practice only a fraction of this mass, initially located within $r \sim r_s$, participates in the process. This is sufficient to change the structure of the central, high-density region.

The general scenario presented here is that of the formation of galaxies by the collapse and fragmentation of gas in DM halos. Within the CDM paradigm, the DM collapse is followed by the

Jeans scale collapse and radiative cooling of the gas. The details of this complicated process are still largely unknown, but the clumpy nature of the gas is unavoidable in the standard cosmogony (Hutchings *et al.* 2000). It is also required within the hierarchical merging scenario of galaxy formation.

For dwarf galaxies, clump masses of 10^5 – 10^6 $M_\odot$ are required for the DF to be efficient in destroying the central cusps. For large galaxies, masses of 10^8 – 10^9 $M_\odot$ are needed. Such massive inhomogeneities are expected to appear after the formation of the first objects, when UV radiation and inefficient cooling would prevent the subsequent collapse of objects with masses smaller than 10^8 $M_\odot$ – 10^9 $M_\odot$, as argued by Haiman, Rees & Loeb (1997). The basic feature assumed here is that the gas component is clumpy and that clumps are bound enough to survive in the DM background for a few dynamical times without colliding or disintegrating. If indeed, at least some of these massive clumps survive long enough and are not tidally stripped or otherwise destroyed, they will dissolve the most massive DM cusps. In this way, more massive halos would end up with the biggest cores — since they initially start with the largest NFW scalelength. This is in line with what is inferred from observations (as shown in section 3). Alternatively, a mass spectrum of these clumps with a lower mass tail can, in principle, be created by a variety of physical processes. The details of such processes are outside the scope of this paper — although in some of the runs we do allow for an exponential cutoff in the gas-DM coupling via DF, thus mimicking a fragmentation process.

If the mechanism described in this paper starts acting early in the history of the hierarchical merging process, when the halo masses are small, proportionately smaller clump masses would be sufficient in changing the CDM halos' central structures — since the efficiency of our mechanism depends on the relative masses of the clumps and halo component. In this case the final core radii and their variation with halo mass will depend on the details of the merging process. The resultant central structure of these halos, however, should still exhibit constant density cores, since these are conserved by the merging process (see, e.g., Pearce, Thomas & Couchman 1993).

The model presented here provides a framework for understanding the possible discrepancy between observations of galaxies and the outcome of N-body simulations. The final dark halo density distributions are well fit by empirical profiles inferred from observations. The less concentrated density profiles may also be relevant to the substructure problem — smaller halos with low density cores would be less likely to survive to be observed today. For simplicity, and in order to emphasize the feasibility of the processes described here — that the energy deposited in the halo is sufficient, given realistic gas mass fraction, in overcoming the effect of the adiabatic contraction and leading to the formation of a significant constant density core — we have considered models with zero net angular momentum. Thus we cannot comment in detail as to the effect of our mechanism on the angular momentum problem present in CDM models of disk formation. In principle dynamical friction may also transfer angular momentum from the baryonic component to the DM one. Our mechanism however is effective only in the central region of galaxies and the clumps are likely to end up in a relatively low angular momentum system, such as a galactic bulge-central mass component. In the outer regions, dynamical friction is not effective. The fate of the gas lumps will be determined by collisions. These will lead to collapse to a preferred plane, accompanied by contraction and spin up. Once this "second generation" material has reached the central regions it is likely to loose less angular momentum to the resulting inner halo — since the latter is less concentrated and has higher angular momentum — than it would by interaction with the original NFW halo. This could lead to less concentrated disks. It is also possible that tidal interactions between the less concentrated halos lead to higher net angular momenta.

We find that, under certain circumstances, the *total* rotation curves can also exhibit a halo-core structure, albeit more modest than the DM alone. As emphasized above, one can also envisage a scenario where the clumps sink to the bottom of the potential well, dissipating their orbital energy by the DF and collisions to form the galactic disk/bulge and the central black hole. Part or most of the gas can subsequently be blown away by positive energy feedback provided by massive star formation and supernovae explosions in the form

of galactic winds. The efficiency of this process should anti-correlate with the depth of the potential well and hence distinguish between dwarf and massive galaxies.

We use a semi-analytical Monte-Carlo approach, based on the Chandrasekhar approximation for the DF drag force in a homogeneous medium of uncorrelated particles. This approximation can be improved by high-resolution simulations in which the super-particles are introduced by construction and where the full N-body interaction, including potentially important global response of the background medium (e.g., Weinberg 2000) is taken into account. N-body simulations of the dynamics of satellite galaxies in massive halos show that the semi-analytical modeling underestimates the DF effect when the satellite mass fraction is $0.05 - 0.2$ (Tormen *et al.* 1998), similar to the fraction of baryonic mass within $r < 10$ in our models. The eventual slowing down of the self-consistent evolution compared to the semi-analytic one in their models is probably due to the decreasing central background density resulting from energy feedback into the background medium from the dissipating satellites, which is not modeled in their semi-analytic calculations. We have also assumed spherical symmetry. Simulated DM halos are found to be triaxial. In such systems the effect of DF is strongly enhanced (Pesce, Capuzzo-Dolcetta & Vietri 1992). Therefore, the effect described in this paper can be probably achieved for substantially smaller clump masses or on smaller timescales.

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